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ANALYSIS OF THE PACOIMA DAM ACCELEROGRAM—SAN FERNANDO, CALIFORNIA, EARTHQUAKE OF 1971

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ABSTRACT

Integrated ground velocities and displacements calculated from the accelerogram recorded at the Pacoima dam site indicate that the strong ground motion was predominately in the vertical and NS direction, in general agreement with the mechanism of faulting as inferred from aftershock studies, and with fault displacements observed in the field. High-frequency peak accelerations of 1.25 g were recorded in two horizontal directions, these being the highest ground accelerations so far recorded for earthquakes. Response spectrum curves calculated from the accelerograms do not show unusual features, and the numerical values are consistent with past experience. The high-frequency, high-amplitude impulsive ground motion associated with the highest peak accelerations did not contribute significantly to the over-all response spectrum values. The presence of the high-frequency motions in the recorded accelerograms is presumably the consequence of the proximity of the recording site to the fault dislocation.

Introduction

The strong earthquake ground motion of the San Fernando, California, earthquake of February 9, 1971 was recorded on over 200 accelerographs of the Southern California strong-motion network. These accelerographs were located at various ground sites, buildings and dams. By number and quality of the records, the instrumental coverage of this earthquake is, by far, the most extensive and complete in the history of strong-motion seismology.

Although this 6.6 magnitude earthquake is not large from the seismological point of view, it was associated with very severe ground motions and must be ranked as a major event from the standpoint of damage and general engineering implications.

The instrumentally-determined focus of the main shock, at a depth of about 13 km, represented the region in which faulting was initiated. The fracture then propagated up and to the south, past and under the Pacoima Dam accelerograph site, and intercepted the surface in the Sylmar-San Fernando area (Figure 1). The Veterans Hospital which collapsed killing 44 people, and the Olive View Hospital which was severely damaged with 3 deaths, were located about 3 km to the north of the surface faulting (Figure 1).

The local severity of shaking in the Sylmar-San Fernando area appears to have been as strong as would be expected for the largest shocks in California, although longer fault breaks would result in greater durations of ground shaking. The idealized empirical relation between magnitude and fault length (Housner, 1970) would predict the fault length for this earthquake to be about 15 km, which is in excellent agreement with the observed surface faulting (Figure 1) and the over-all dislocation size outlined by the distribution of aftershocks (Figure 2). For an earthquake of magnitude 8 or greater, the surface faulting might extend for several hundreds of kilometers and as a result the strong ground motion would last several times longer than the motion recorded during the San Fernando earthquake.

The Accelerograph Site

Because of the importance of the Pacoima Dam record, which was obtained virtually at the center of the event, and because of the rather special nature of the site, it is believed that a relatively detailed description of the site and of the instrument installation is justified.

Figure 3 shows an oblique aerial photograph looking south over the Pacoima Dam site with the San Fernando Valley in the distance. The location of the AR-240 accelerograph at Pacoima Dam is shown, and the locations of the two heavily-damaged hospitals are indicated in the background. Figure 4 shows a close-up view of the dam, with the location of the accelerograph on a rocky spine adjacent to the dam abutment

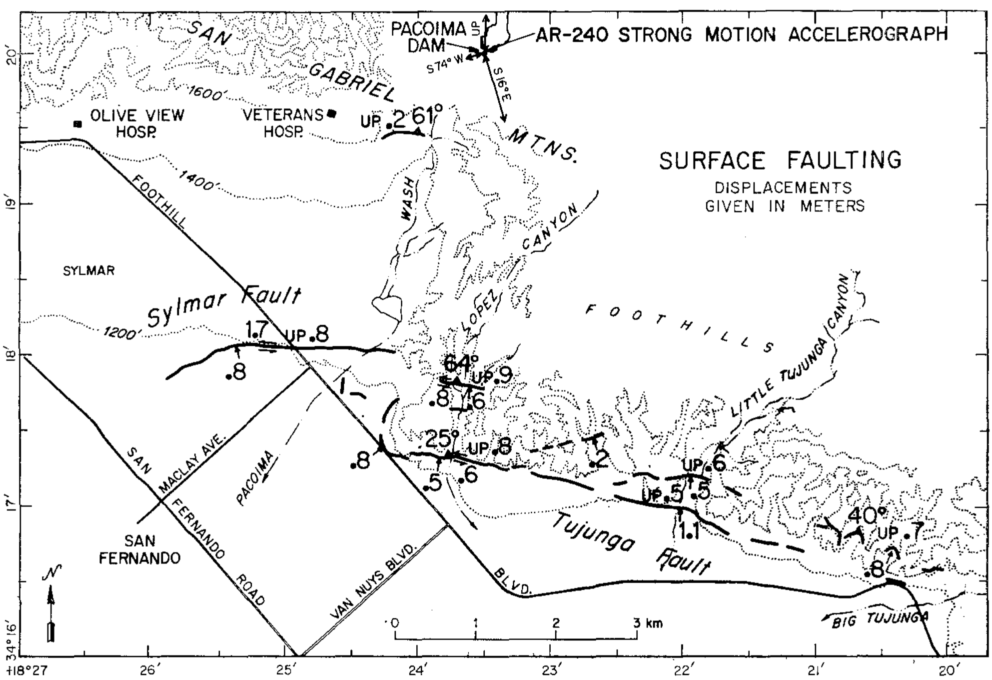

Fig. 1. Surface faulting in the Sylmar-San Fernando-Tujunga area (reproduced by permission from the Division of Geological and Planetary Sciences, California Institute of Technology, and Kamb *et al.*, 1971), and its relation to the recorded strong ground motion at the Pacoima Dam.

indicated. Figure 5 shows a view of the circular instrument house seen from below on the dam, and Figure 6 is a view of the dam and the instrument house from above looking north. In both of these figures, extensive cracking of the gneissic granite-diorite rock will be noted. Many of the cracks penetrate through the smooth gunite coating into the rock below.

It is not known, however, to what extent the surface fractures of the gunite coating reflect the conditions of the major rock mass below. Relatively small cracks of the dimensions of the gunite fractures would be associated with higher frequencies than those involved in the approximately 10 cps motions observed on the record (Figures 11, 12 and 13). The extent to which presently unknown details of the ridge structure may influence the recorded motions is for the time being a matter for speculation only.

As can be seen in Figure 5, about 5 m to the west of the accelerograph, a small rock slide occurred (about 5–10 m^3) during the earthquake, which fortunately was not large enough to disturb the accelerograph foundation. As will be seen in Figure 7, one of the cracks penetrated into the foundation of the instrument house, although as will be noted, the instrument pier itself, which was separated by an inch or so from the foundation of the circular house, was not cracked. As of two months after the earthquake, changes in the configuration of these foundation cracks indicate that long-term motion of some kind is continuing. After the earthquake, the instrument mounting pier was still solidly attached to the foundation rock, and the mounting bolts attaching the accelerograph to the pier were tight and undisturbed. The only sign of disturbance was

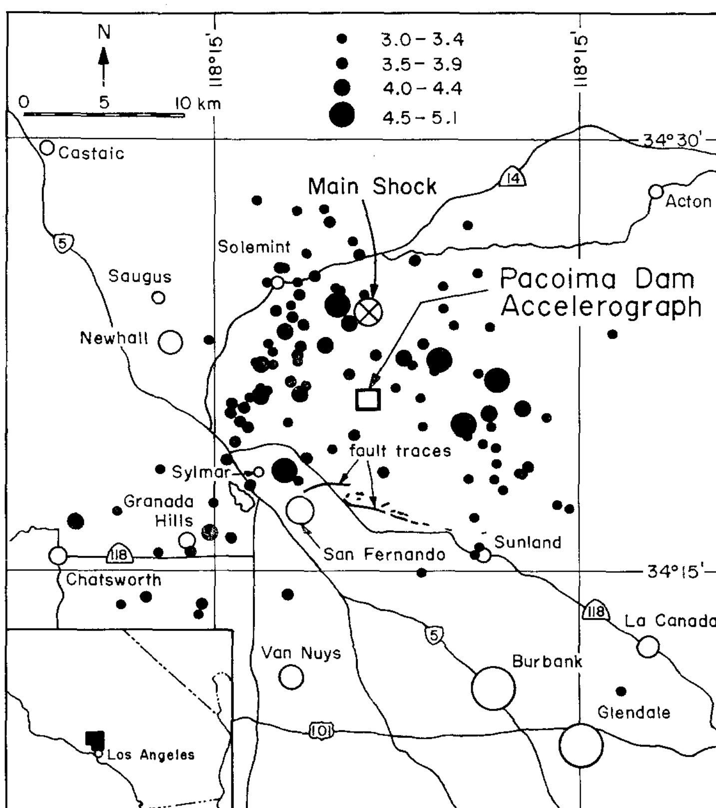

FIG. 2. Map of the epicenters of the main shock and representative aftershocks of the San Fernando earthquake of magnitude 3.0 and greater, through February 23, 1971 (reproduced by permission from the Division of Geological and Planetary Sciences, California Institute of Technology, 1971).

a small permanent tilt of the instrument during the earthquake, which could be estimated to be of the order of 0.°5 in the NW direction. The amount of this permanent tilt could be estimated with fair accuracy from the adjustments required after the earthquake to re-level the accelerograph (Dielman, personal communication). A view of the accelerograph mounted on its concrete pedestal within the circular house after the earthquake is shown in Figure 8.

A plan view of the dam, and the abutment area, with the instrument locations indicated, is shown in Figure 9. Also shown is the location of the Wilmot Seismoscope on the crest of the dam. During the first few seconds of earthquake motion, the motion of the crest of the dam was so severe that the seismoscope glass record plate was dislodged from its retaining ring, so that no useable seismoscope record was obtained.

As a further indication of the setting of the site within the aftershock region, Figure 2 may be referred to. The site is approximately 8 km south of the instrumentally-determined epicenter and is nearly in the center and above the tentative fault disloca-

FIG. 3. Oblique aerial view looking southwest over the Pacoima Dam site.

tion surface striking N72°W and dropping about 45° toward the north (Kamb, *et al.*, 1971).

ACCELEROGRAPH PERFORMANCE

The AR-240 strong-motion accelerograph at the Pacoima Dam site records two horizontal and one vertical components of acceleration on 12-in-wide photographic paper. The accelerograph transducers have natural frequencies of about 19 cps and damping of approximately 60 per cent critical (Hudson, 1970). The instrument is one of several owned by the Los Angeles County Flood Control District and is a part of the Southern California strong-motion accelerograph network maintained by the Seismological Field Survey of the NOAA National Ocean Survey.

FIG. 4. Close view of the Pacoima Dam.

As mentioned above, after the earthquake, the accelerograph foundation remained tilted through a small angle which was estimated to be about 0°.5. This small angle was sufficient to actuate the starting pendulum and the instrument recorded continuously for some 6 min until it ran out of paper. During this interval, at least 30 aftershocks were recorded. In one sense, the small permanent tilt of the foundation can be considered to be a fortunate occurrence, since it permitted this recording of the beginning of the aftershock sequence, and indicated the exact sequence of aftershock events in the epicentral region. These details of the aftershock sequence will be of importance in investigating the mechanism of energy release.

In order to check the instrument performance, tilt, free vibration, and damping tests were performed after the earthquake. The tilt test showed that the sensitivity of

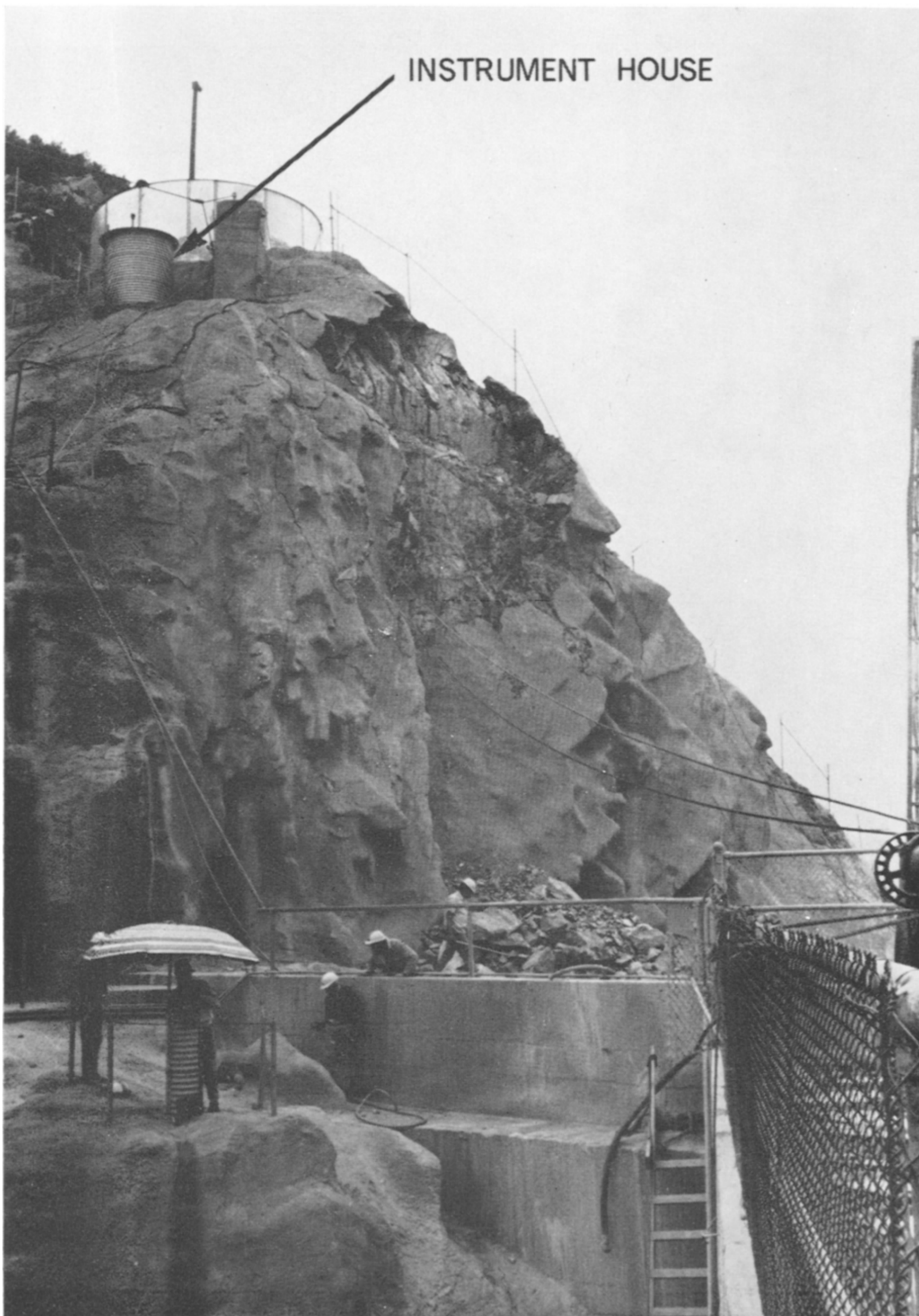

FIG. 5. Strong-motion AR-240 accelerograph site and the small rock slide.

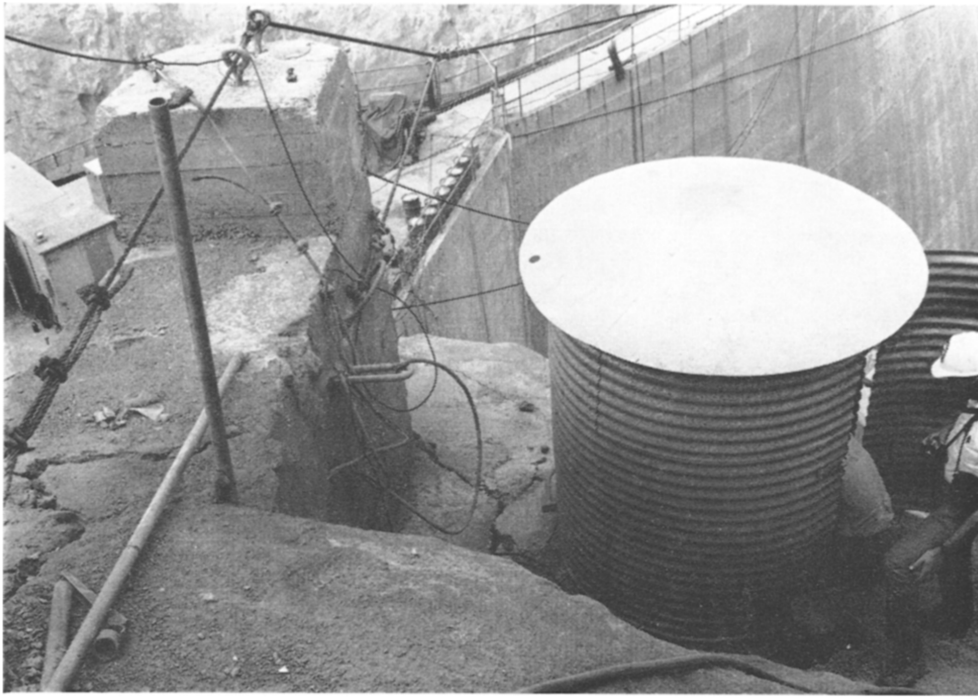

FIG. 6. View of the dam and the instrument site.

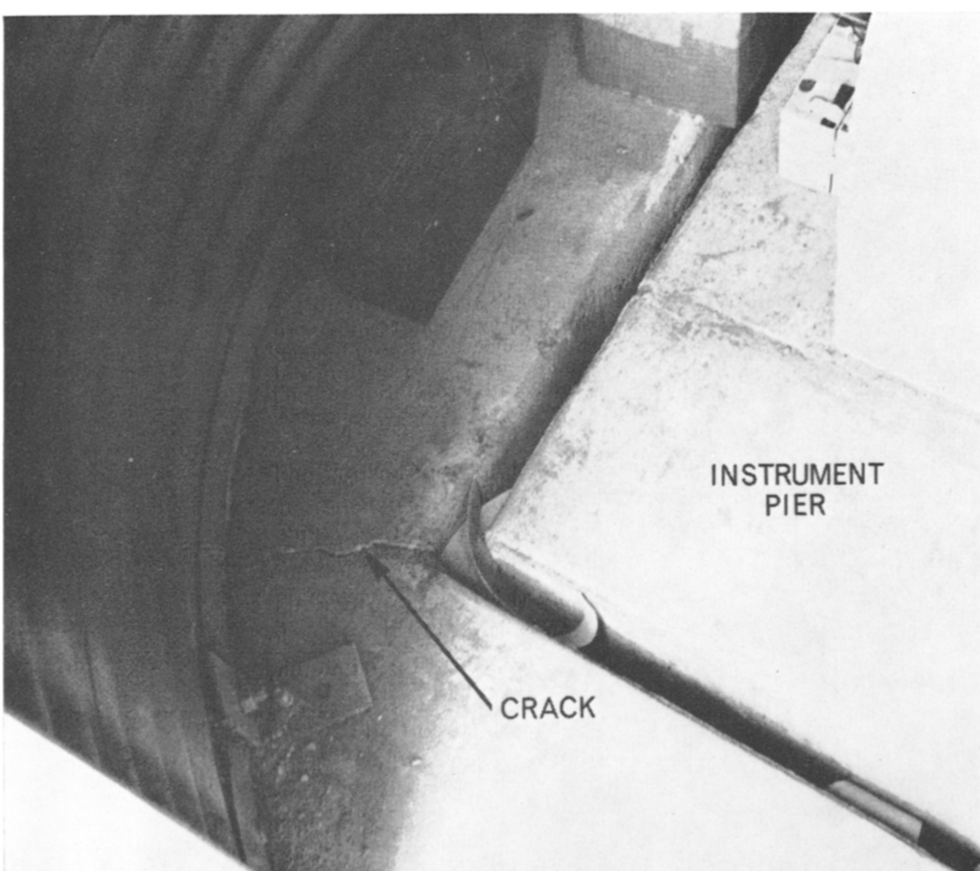

FIG. 7. Cracks in the foundation of the instrument house.

the accelerograph had not changed significantly. The alignment of the transducer axes relative to the instrument base was also checked during the tilt test (Trifunac and Hudson, 1970). It was found that the two horizontal transducers were well within a

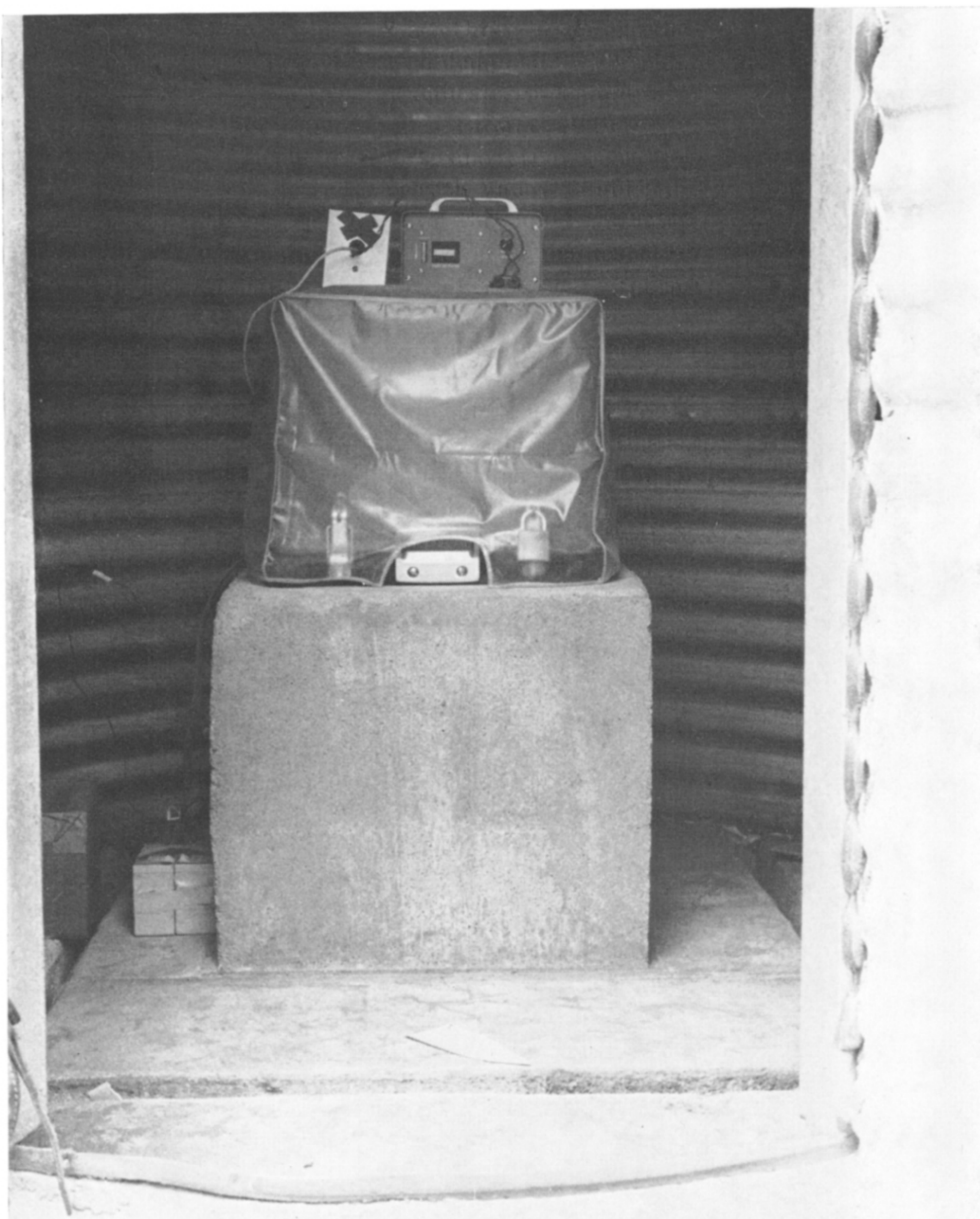

FIG. 8. AR-240 accelerograph after the earthquake.

1° alignment. The vertical transducer sensitivity vector was about 5° from the vertical in the longitudinal direction.

Judging from the point of view of the accuracy of the typical strong-motion accelerograph (Trifunac and Hudson, 1970), it may be concluded that the AR-240 accelerograph at the Pacoima Dam site performed essentially to specifications and that the recorded acceleration traces may be adopted as representative of the actual motion of the instrument foundation. The peak acceleration values remained on scale on the photographic paper, and there is no evidence of appreciable nonlinear response at the maximum amplitudes involved.

After the earthquake, the instrument base was tilted in approximately the NW direction, relative to its position prior to the earthquake. Since the preliminary calculations

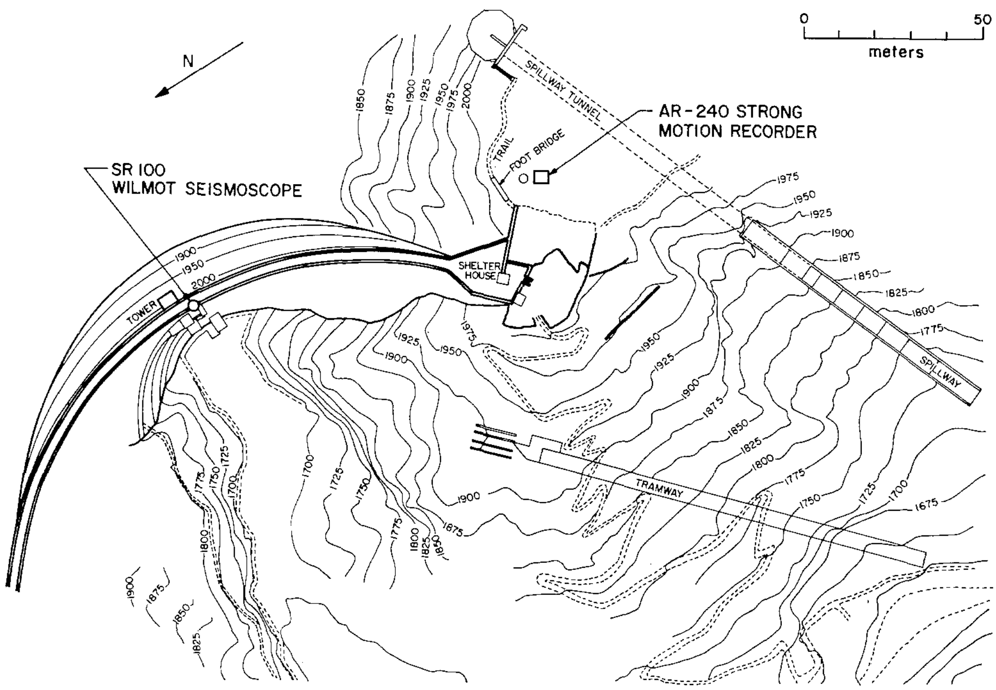

FIG. 9. Pacoima Dam site with AR-240 strong-motion accelerograph and SR 100 Wilmot Seismoscope.

TABLE 1

RESULTS OF TESTS TO ASCERTAIN DISPLACEMENT LIMITS

Direction of Baseline Shift for Tilt in NW Direction	Baseline Shift (cm/sec^2)
N 74 E	13.3
Down	7.7
N 16 W	2.6

of the ground displacement indicated a significant shift in the accelerograph base line, clearly a consequence of such tilt, tests were conducted to ascertain likely limits for such displacements. The accelerograph was tilted in the NW direction through an angle which just closed the starter pendulum gap, and in this way a lower bound estimate of the acceleration base-line shift could be determined. The results of this test are given in Table 1.

The integration of the digitized accelerograms (Figure 10) including the first aftershock (about 42 sec) indicates that the tilt must have occurred within the first 10 to 15 sec of the strong motion. This can be concluded from the behavior of the integrated

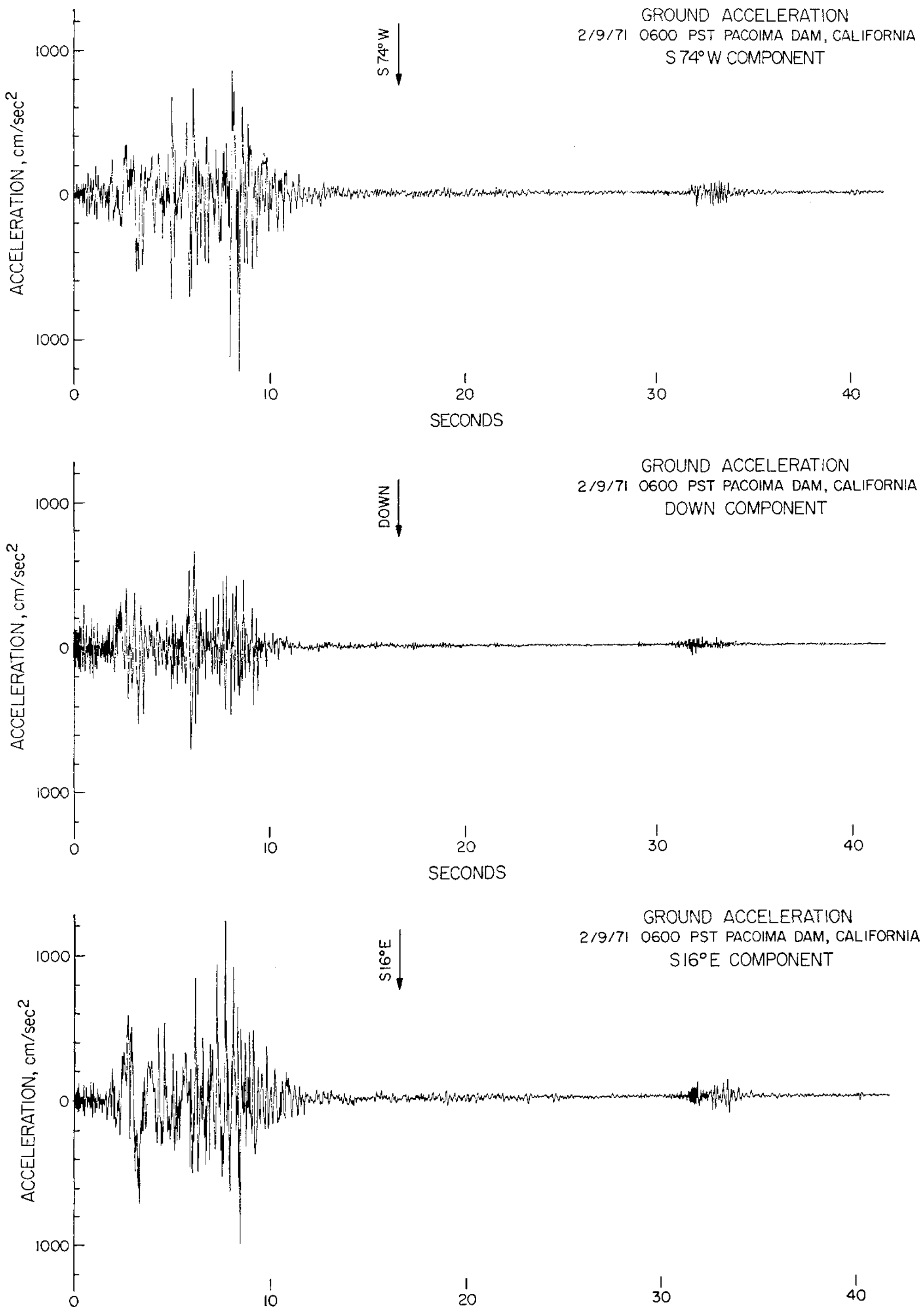

FIG. 10. Plot of digitized accelerograms recorded at the Pacoima Dam.

velocity curves. If a straight line fitted to the velocity curves (Trifunac, 1970), over the interval between 12 and 42 sec, is extrapolated back to the zero time, the resulting displacement curves indicate the permanent displacements after the earthquake as shown in Table 2.

It might be tempting to interpret these results in terms of the observed surface fault displacements (Figure 1, Kamb *et al.*, 1971). However, if it is assumed that the tilting indeed took place during the first 10 sec, the lower bounds for the "permanent displacements" obtained only from the tilt would be those shown in Table 3 (based on data of Table 1).

For this calculation it was assumed that the acceleration zero base line is determined by its fixed position after the tilt is completed, 10 sec after the instrument has triggered, and that the tilt occurred uniformly over the 10 sec interval. Comparing the amplitudes

TABLE 2
INDICATED PERMANENT DISPLACEMENTS AFTER THE EARTHQUAKE

Permanent Displacement in Direction	Permanent Displacement Amplitude (m)
N 74 E	1.0
Up	1.3
S 16 E	1.7

TABLE 3
VALUES BASED ON ASSUMPTION THAT TILTING OCCURRED DURING FIRST 10 SECONDS

Permanent Displacement in Direction	Lower Bounds on Permanent Displacement Amplitudes Caused by Tilt (m)
S 74 W	4
Up	3
S 16 E	1

given in Tables 2 and 3, it may be concluded that the tilt was large enough to prevent any estimation of the permanent displacements associated with the earthquake.

DATA PROCESSING AND GROUND MOTION CALCULATIONS

Figure 10 is a plot of the first 42 sec of the digitized accelerograms including the first aftershock. The strong motion representing the main energy release lasted for about 7 sec and the first aftershock was recorded about 29 sec after the instrument was triggered. The first 15 sec of the acceleration were chosen for the analysis of ground motion.

The AR-240 accelerogram was digitized at Caltech on a Benson Lehner 099D data reducer and processed by the standard methods developed in recent years for strong-motion accelerogram analysis (Hudson *et al.*, 1969). The quality of the original record was excellent. The trace was clear and continuous with the exception of one 1.25 g peak on the S16°E component at 7.6 sec. At this point, the trace was lost above the 1 g level and had to be extrapolated. Because of the excellent photographic quality of the trace, this extrapolation could be carried out with confidence. The error in the peak is believed to be less than 0.1 g, which would not appreciably influence any calculations based on the accelerogram. The digitization of the Pacoima Dam accelerogram is

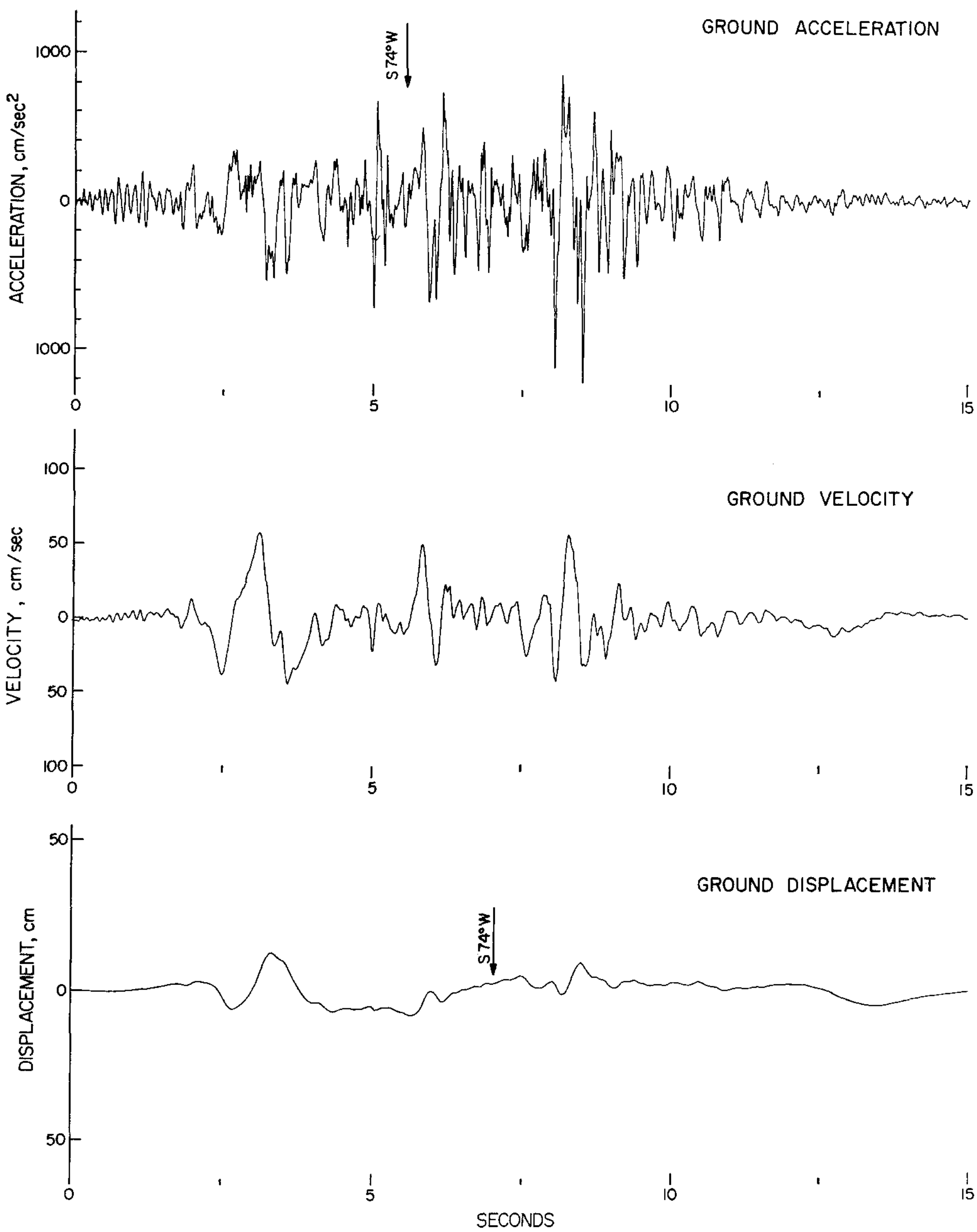

FIG. 11. S74°W motion, Pacoima Dam—San Fernando, California, Earthquake February 9, 1971, 6:00 P.S.T.

believed to be as accurate as may be achieved by presently available techniques and equipment.

The base-line correction was performed by high-pass filtering the uncorrected data above the frequency 0.07 cps. This means that all periods longer than approximately

16 sec have been removed from the record, and, hence, that no information on permanent displacements is to be expected from the analysis. This filtering procedure, and the least-square fitting of a straight line to the ground velocity, which gives an esti-

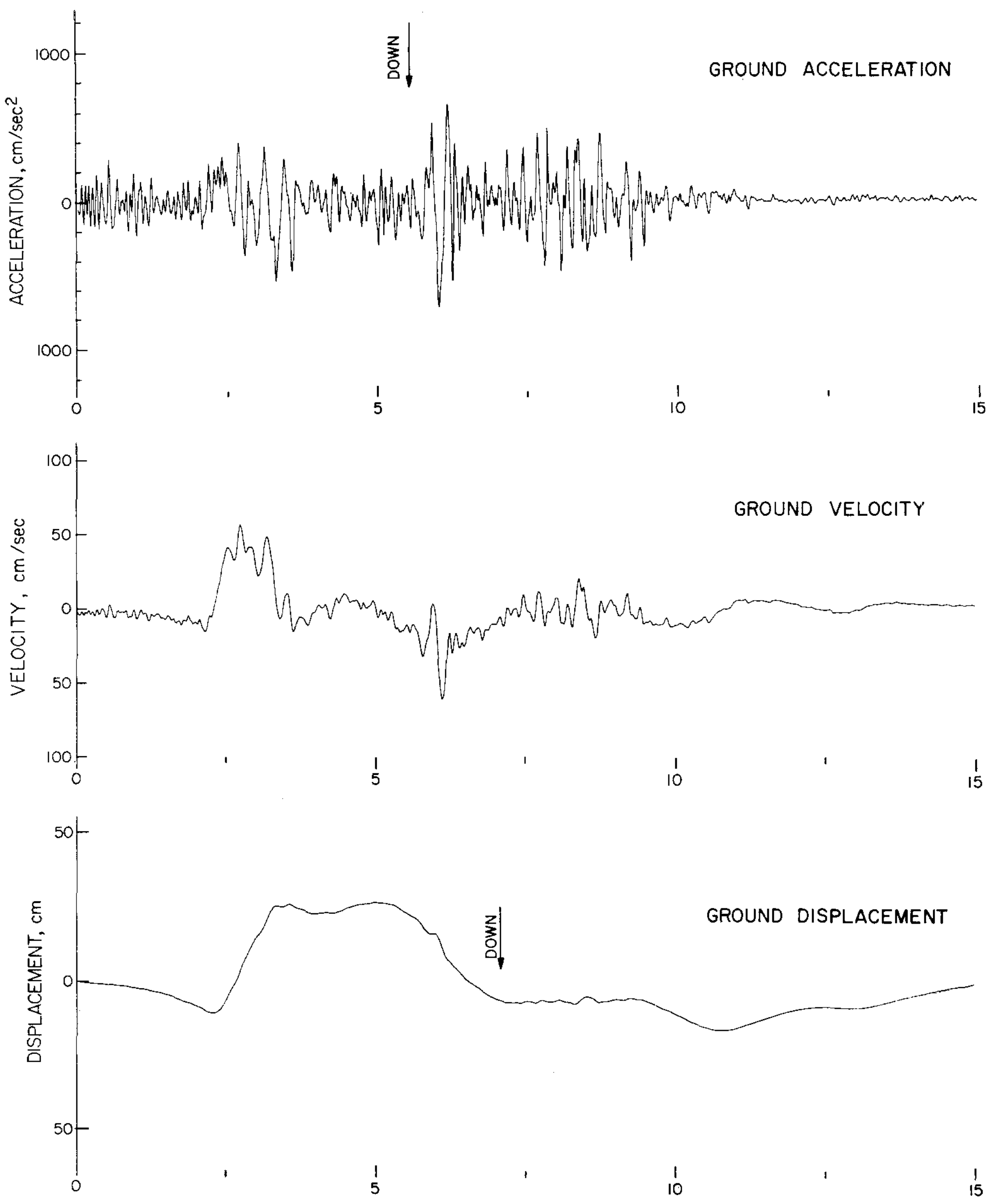

FIG. 12. Down motion, Pacoima Dam—San Fernando, California, Earthquake, February 9, 1971, 6:00 P.S.T.

mate of the initial velocity, constitute a new method recently proposed for standard base-line correction of the strong-motion accelerograms (Trifunac, 1970). The resulting acceleration, velocity and displacement curves are shown for the three recorded components in Figures 11, 12 and 13. As may be seen in these figures, the maximum acceleration is 1.25 g for both horizontal components and 0.70 g for the vertical component, and the peak velocity is 115 cm/sec.

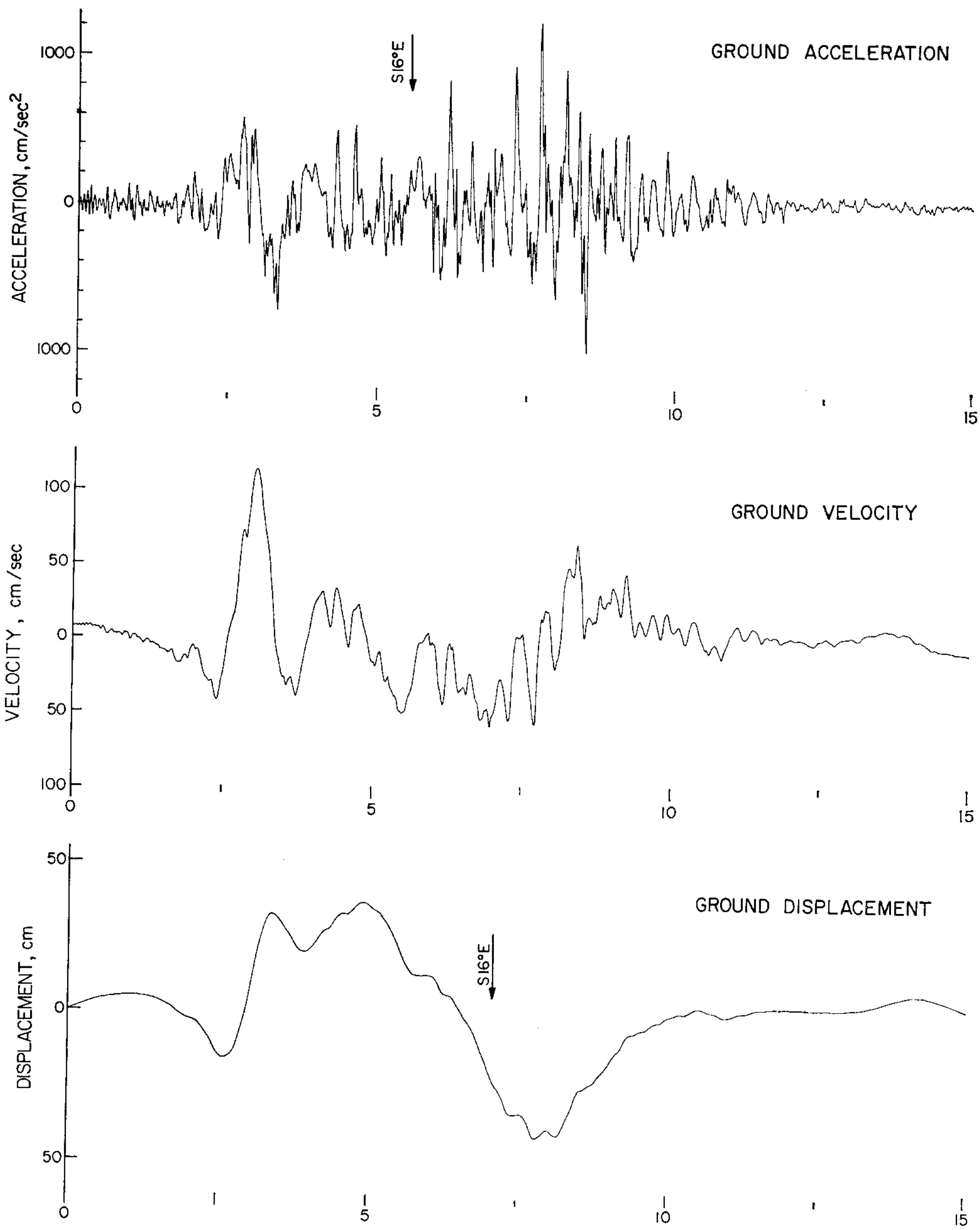

FIG. 13. S16°E motion, Pacoima Dam—San Fernando, California, Earthquake February 9, 1971, 6:00 P.S.T.

As already mentioned, the tilting of the instrument base must have taken place during the first 15 sec of the strong motion. Thus, the displacements in Figures 11, 12, and 13 may contain an unknown contribution from the tilting of the instrument in addition to the actual ground motion. Nevertheless, the computed ground motion

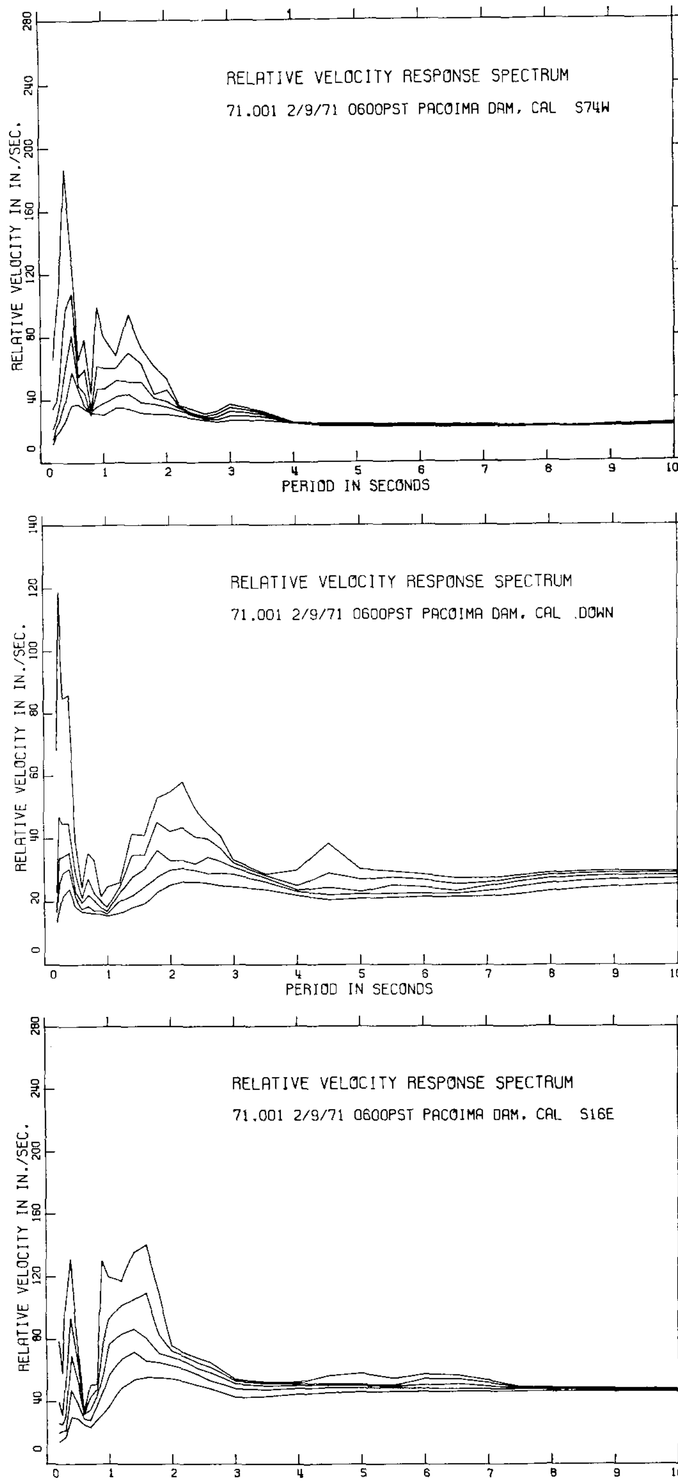

FIG. 14. Relative velocity response spectra, Pacoima Dam. The curves are for 0, 2, 5, 10, and 20 per cent damping.

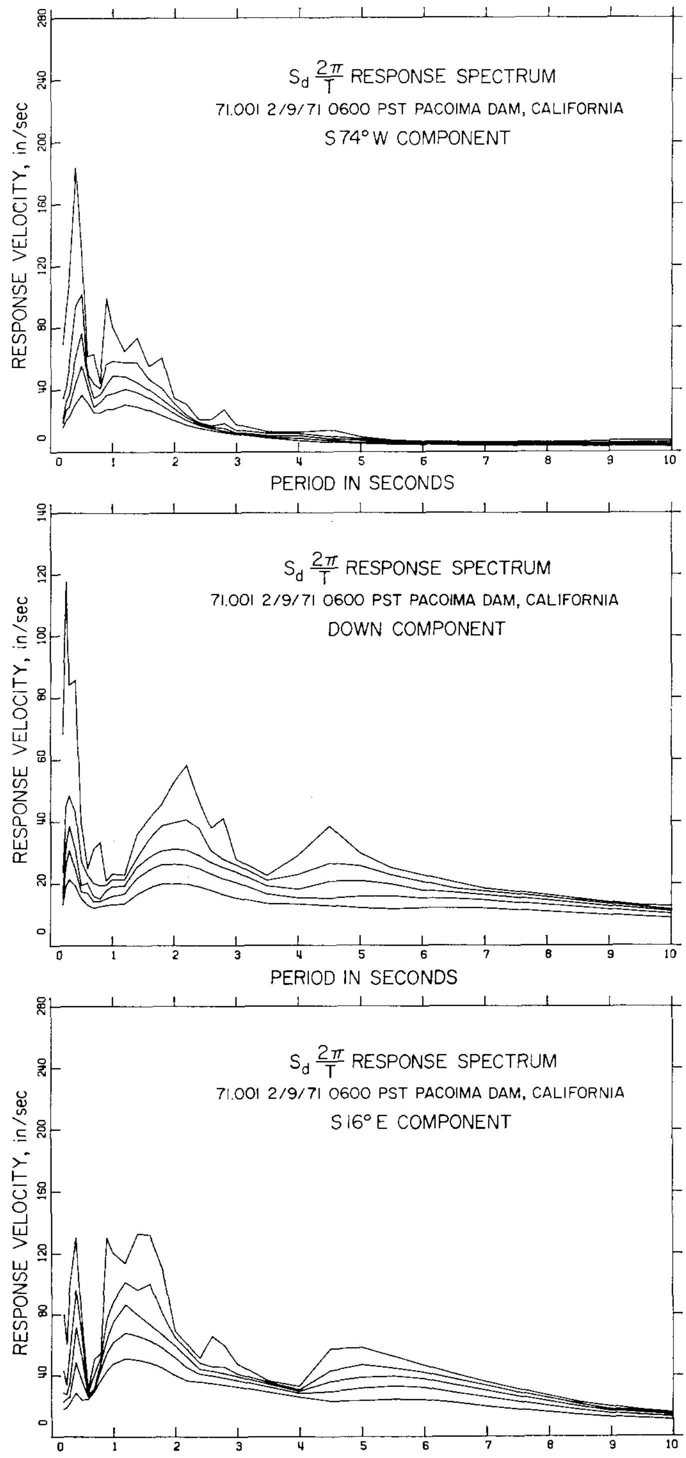

FIG. 15. $S_d 2\pi/T$ response spectra, Pacoima Dam. The curves are for 0, 2, 5, 10, and 20 per cent damping.

indicates that the biggest displacements were vertical and in the north-south direction, in general agreement with observed surface faulting (Figure 1).

In terms of acceleration amplitude, the ground motions recorded at the Pacoima Dam site are the largest so far measured during any earthquake. The relatively short duration of the severe shaking is a consequence of the short fault rupture.

Response Spectra

The computed relative velocity and $S_d 2\pi/T$ response spectra (S_d = displacement spectrum; T = period) are shown in Figures 14 and 15. For each acceleration component, the response spectrum curves were calculated for 0, 2, 5, 10 and 20 per cent of critical damping. As expected, the relative velocity and $S_d 2\pi/T$ spectra are very similar for short periods while the $S_d 2\pi/T$ spectrum falls off more rapidly for longer periods. It may be recalled that the zero damped relative velocity response spectrum is an approximate representation of the Fourier amplitude spectrum of the accelerogram.

TABLE 4

Comparison of Earthquake Data

Earthquake	Magnitude	Distance* (km)	Peak Acceleration (g)	Peak Velocity (in/sec)	Approx. S_V for $T > 3$ sec (in/sec)
San Fernando, 1971	6.6†	5	1.25	45	50
El Centro, 1940	6.4‡	10‡	0.33	17	30
Parkfield, 1966	5.5§	0.2‖	0.50	28	30
Koyna, India, 1967	6–6.3¶	5	0.63**	9	15

* Estimated distance from accelerograph to portion of fault surface associated with maximum energy release.

† Division of Geological and Planetary Sciences, California Institute of Technology (1971).

‡ M. D. Trifunac and J. N. Brune (1970).

§ G. W. Housner and M. D. Trifunac (1967).

‖ K. Aki (1968).

¶ H. G. Gupta, B. K. Rastogi, and H. Narain (1971).

** J. Krishna, A. R. Chandrasekaran, and S. S. Saini (1969).

The spectrum curves for the horizontal S16°E and S74°W components show peaks at about 0.4- and 1.4-sec periods, while the spectra for the vertical component indicates predominant periods near 0.3 and 2 sec. The short duration of the strong motion is reflected in the nature of the response spectra of Figure 14, which shows a relatively flat character for periods longer than 5 or 6 sec. In the period range 0.5 to about 3 sec, the spectral amplitudes are similar to those calculated for the El Centro 1940 accelerogram (Alford *et al.*, 1951). The high-frequency spectral amplitudes in the Pacoima Dam record are not incompatible with past experience. Similar high-frequency characteristics can be noted on records from the Parkfield, California, earthquake of June 27, 1966, (Housner and Trifunac, 1967) and for the Koyna, India, earthquake of December 10, 1967 (Gupta, *et al.*, 1971). Direct comparisons with these other earthquakes are difficult because of significant differences in the location of the accelerographs, with respect to the pattern of faulting, and in the sizes of the events. Table 4 gives an approximate idea of such comparisons.

The strong earthquake ground motion recorded during the Parkfield, California, 1966 earthquake (Housner and Trifunac, 1967) may be considered as a typical example of a short, impulsive-type ground motion. On the other hand, the motion recorded at El Centro during the Imperial Valley, California, 1940 earthquake (Trifunac and Brune, 1970) is an example of the relatively long shaking produced by multiple events successively occurring along a fault about 40 miles long. The ground acceleration, velocity, and displacement curves plotted in Figures 11, 12 and 13 show that from the engineering point of view, the duration of the energy release during the San Fernando earthquake is somewhere between that of Parkfield and El Centro.

The Engineering Significance of the Pacoima Results

One of the important facts about strong earthquake ground motion is that large ground acceleration amplitudes in themselves do not necessarily indicate severe damage to structures. It is also clear that high spectral accelerations do not always tell the whole story. The response spectrum curves alone cannot give a complete picture of the effects of the time duration of the acceleration history. These facts have been clearly demonstrated by the spectra calculated for the Parkfield earthquake (Housner and Trifunac, 1967) and the El Centro earthquake (Alford *et al.*, 1951). Thus the high spectral amplitudes in Figures 14 and 15 do not necessarily mean that this motion was very destructive for structures of all types. Pacoima Dam, for example, apparently suffered no significant damage.

The San Fernando earthquake with strong motion lasting about 7 sec now becomes an excellent example of a strong ground acceleration of short to moderately long duration. If the shaking had continued for another few seconds, much greater damage would have resulted, and many buildings and bridges so far only partially damaged would have collapsed. It is mainly this effect of the duration of shaking on structural damage that calls for detailed investigations of the pattern of earthquake energy release in time.

Acknowledgments

The existence of the Pacoima accelerogram is a tribute to the success of the long-range program establishing the Southern California strong-motion accelerograph network under the supervision of W. K. Cloud, Chief of the Seismological Field Survey, and R. P. Maley, in charge of the Los Angeles office, of the NOAA National Ocean Survey.

We much appreciate the numerous contributions of Richard J. Dielman of the Earthquake Engineering Research Laboratory of the California Institute of Technology to all aspects of the program of instrument installation, servicing, record collection and development, and laboratory instrument evaluation.

V. Perez of the NOAA Seismological Field Survey assisted with the digitization of the Pacoima accelerogram; and Dr. A. G. Brady of the Caltech group carried out details of the data processing.

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Special thanks are due to Engineering Mechanics Division of the National Science Foundation for their very prompt action after the earthquake in making support available to carry out data processing of the unprecedented body of strong-motion accelerograms. This research was also supported in part by the National Science Foundation Grant GA 22709 to the Lamont-Doherty Geological Observatory of Columbia University.

References

Aki, K. (1968). Seismic displacements near a fault, *J. Geophys. Res.* **73**, 5359–5376.

Alford, J. L., G. W. Housner, and R. R. Martel (1951). *Spectrum Analysis of Strong-Motion Earthquakes*, California Institute of Technology, Pasadena.

Division of Geological and Planetary Sciences, California Institute of Technology (1971). Preliminary seismological and geological studies of the San Fernando, California, Earthquake of February 9, 1971, *Bull. Seism. Soc. Am.* **61**, 491–495.

Gupta, H. K., B. K. Rastogi, and H. Narain (1971). The Koyna Earthquake of December 10, 1967: A multiple seismic event, *Bull. Seism. Soc. Am.* **61**, 167–176.

Hanks, T. C., T. H. Jordan, and J. B. Minster (1971). Precise locations of aftershocks of the San Fernando Earthquake 2300 (GMT) February 10 to 1700 February 11, 1971, U. S. Geological Survey, *Professional Paper 733*, pp. 21–23.

Housner, G. W. and M. D. Trifunac (1967). Analysis of accelerograms—Parkfield Earthquake, *Bull. Seism. Soc. Amer.* **57**, 1193–1220.

Housner, G. W. (1970). Strong ground motion, Chapter 4 in *Earthquake Engineering*, R. L. Wiegel, Editor, Prentice-Hall, 1970.

Hudson, D. E., A. G. Brady, and M. D. Trifunac (1969). Strong Motion Earthquake Accelerograms, Digitized and Plotted Data, Vol. 1, Earthquake Engineering Research Laboratory, *EERL 69-20*, California Institute of Technology, Pasadena.

Hudson, D. E. (1970). Ground motion measurements, Chapter 6 in *Earthquake Engineering*, R. L. Wiegel, Editor, Prentice-Hall, 1970.

Kamb, B., L. T. Silver, M. J. Abrams, B. A. Carter, T. H. Jordan, and J. B. Minster (1971). Pattern of Faulting and Nature of Fault Movement in the San Fernando Earthquake. U. S. Geological Survey, *Professional Paper 733*, pp. 41–54.

Krishna, J., A. R. Chandrasekaran, and S. S. Saini (1969). Analysis of Koyna Accelerogram of December 11, 1967. *Bull. Seism. Soc. Am.*, **59**, 1719–1731.

Trifunac, M. D. and J. N. Brune (1970). Complexity of energy release during the Imperial Valley, California, Earthquake of 1940, *Bull. Seism. Soc. Am.* **60**, 137–160.

Trifunac, M. D. and D. E. Hudson (1970). Laboratory evaluations and instrument corrections of strong-motion accelerographs, Earthquake Engineering Research Laboratory, *EERL 70-04*, California Institute of Technology, Pasadena.

Trifunac, M. D. (1970). Low frequency digitization errors and a new method for zero baseline correction of strong-motion accelerograms, Earthquake Engineering Research Laboratory, *EERL 70-07*, California Institute of Technology, Pasadena.

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